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Investigating the Use of WAAS as a Navigational Tool for Coast Guard and Civilian Maritime Use

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ABSTRACT

Since 2003, the Federal Aviation Administration (FAA) has employed the Wide Area Augmentation System (WAAS) for precision approaches to airports and navigational use for aircraft over the continental United States, adjacent ocean regions, and parts of Alaska. This was due in part to GPS/DGPS not meeting the FAA's strict guidelines for accuracy, integrity, and availability. Currently, the FAA rates WAAS for 250ft and above the surface of the earth; this 250-foot barrier ensures 100% coverage over the United States from two existing INMARSAT satellites. Because of this height restriction, the Coast Guard has not accepted WAAS as an individual stand-alone source of navigation for military and civilian use.

In 2005, the FAA plans on launching additional geostationary satellites to increase system redundancy and provide overlapping coverage [1]. By placing one to three more satellites due south of the United States, it might be possible to provide the coverage needed for the maritime community to use WAAS as a primary form of navigation at ground level. The current system of two satellites does not provide double or even single coverage in parts of the United States at ground level due to line of sight issues. By adding more satellites, the 250-foot barrier might be able to be brought down and double coverage for the United States might be possible in all navigable areas.

This paper reports on a project to develop software tools to predict coverage of WAAS satellites (both existing and future) at user selectable locations in the continental United States. To account for topographical features, the Digital Terrain Elevation Data (DTED) Level 1 database with a spacing of 3 arc seconds (or 100 meter resolution) is incorporated into the tool. The results of the predictions are compared to actual field measurements made during 2004 as part of a DGPS/WAAS Accuracy and Availability Study conducted by John J. McMullen Associates in support of the U.S. Coast Guard Academy.

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14. ABSTRACT

Since 2003, the Federal Aviation Administration (FAA) has employed the Wide Area Augmentation System (WAAS) for precision approaches to airports and navigational use for aircraft over the continental United States, adjacent ocean regions, and parts of Alaska. This was due in part to GPS/DGPS not meeting the FAA?s strict guidelines for accuracy, integrity, and availability. Currently, the FAA rates WAAS for 250ft and above the surface of the earth; this 250-foot barrier ensures 100% coverage over the United States from two existing INMARSAT satellites. Because of this height restriction the Coast Guard has not accepted WAAS as an individual stand-alone source of navigation for military and civilian use. In 2005, the FAA plans on launching additional geostationary satellites to increase system redundancy and provide overlapping coverage [1]. By placing one to three more satellites due south of the United States, it might be possible to provide the coverage needed for the maritime community to use WAAS as a primary form of navigation at ground level. The current system of two satellites does not provide double or even single coverage in parts of the United States at ground level due to line of sight issues. By adding more satellites, the 250-foot barrier might be able to be brought down and double coverage for the United States might be possible in all navigable areas. This paper reports on a project to develop software tools to predict coverage of WAAS satellites (both existing and future) at user selectable locations in the continental United States. To account for topographical features, the Digital Terrain Elevation Data (DTED) Level 1 database with a spacing of 3 arc seconds (or 100 meter resolution) is incorporated into the tool. The results of the predictions are compared to actual field measurements made during 2004 as part of a DGPS/WAAS Accuracy and Availability Study conducted by John J. McMullen Associates in support of the U.S. Coast Guard Academy.

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INTRODUCTION

On July 10th 2003, WAAS was put into commission by the Federal Aviation Administration for precision approaches to airports and navigational use for aircraft over the continental United States, adjacent ocean regions, and parts of Alaska. This was done to meet the demands of high accuracy while in flight that DGPS/GPS could not provide. WAAS was able to produce a guaranteed position for the aircraft within 3-7 meters initially and was used from 350 feet and above the surface of the Earth. In late 2003, the height above ground limit was reduced to 250 feet. This 250-foot barrier ensures 100% coverage over the United States for all aircraft from two INMARSAT satellites [2,3].

WAAS is currently undergoing upgrades to make it more reliable. Since there are only two satellites being used right now, if one was to go down or be taken off line for any reason one of the coasts would be affected depending upon which satellite. In 2005 and 2006, the FAA plans on launching three more geostationary satellites over the U.S. to provide more redundancy and overlapping coverage [4].

By placing from one to three additional satellites almost due south of the United States, it might be possible to provide the coverage needed to the maritime community to use WAAS as a primary form of navigation. The current system of two satellites does not provide double or even single coverage in some parts of the United States due to line-of-sight issues. By adding more satellites the 250-foot barrier might be able to be brought down and double coverage for the United States might be possible in all navigable areas.

The primary focus of this project was to develop a MATLAB® Graphical User Interface (GUI) tool that would use Digital Terrain Elevation Data (DTED) Level 1 to provide a precise theoretical model of WAAS coverage for the continental United States taking into account the effects of terrain – both altitude itself and line of sight issues – and testing this model at selected locations within CONUS.

METHODOLOGY

We begin the discussion with a description of the trigonometry of the situation. Consider a plane intersecting the Earth so that it passes through the three points of the Earth's center, the user's position, and the satellite's position. The relative positions of these objects are shown in the plane diagram of Figure 1. In this diagram, the circle represents the Earth at sea level with radius r, the altitude to the satellite above sea level is marked h_s, the dotted line tangent to the Earth at the user's position shows the horizon, and relative locations of the user and the satellite is described by the angle α. Using spherical trigonometry (Napier's rules), this angle can be computed from the latitudes and longitudes of the user and satellite

$$\alpha = \cos^{-1}\left(\cos(\Delta_{lat})\cos(\Delta_{lon})\right)$$

in which Δ_{lat} and Δ_{lon} are the differences in the user's and satellite's latitudes and longitudes, respectively.

The value of interest here is the elevation angle from the user to the satellite, marked as β in Figure 1. In other words, if β > 0, then the satellite is visible to the user. Using some simple trigonometry (extend the ray passing through the user, as shown in Figure 2, to form a right triangle with the satellite) this can be computed as

$$\beta = \tan^{-1}\left(\frac{(r+h_s)\cos\alpha - r}{(r+h_s)\sin\alpha}\right)$$

The presented equations for α and β allow us to begin to understand the effects of terrain on satellite visibility.

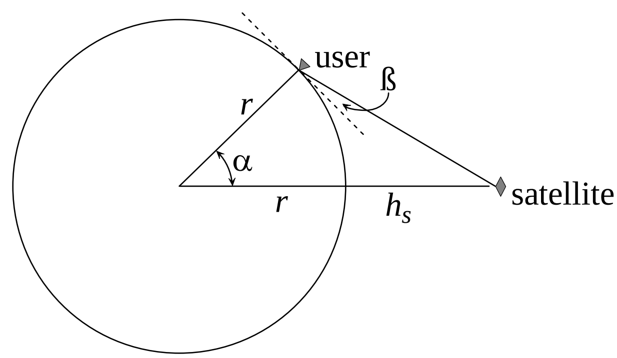

Figure 1 – A planar view of the user and satellite.

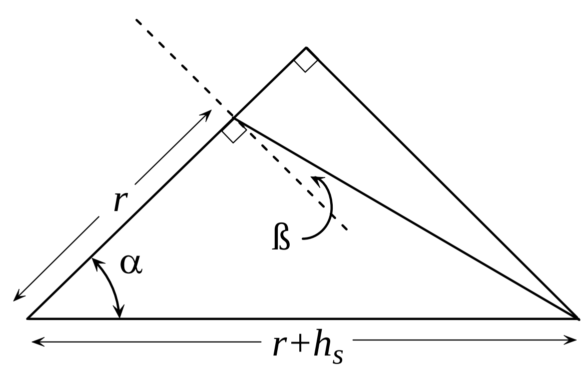

Figure 2 – Solving for the elevation angle.

<u>Altitude Effect Only</u>

Our first consideration of the effects of terrain on elevation to the satellite involves examining the effects of non-zero altitude. Specifically, consider the situation represented in Figure 3. For the more general case of the user at some other altitude than sea level, say h_u, the expression for elevation angle becomes

$$\beta_a = \tan^{-1}\left(\frac{(r+h_s)\cos\alpha-(r+h_u)}{(r+h_s)\sin\alpha}\right)$$

and it is clear from Figure 3 that this angle decreases with increasing altitude. Upon closer examination, however, we observe that the change in elevation angle for the WAAS satellite is insignificant. Specifically, using realistic values of r = 6378 km and h_s = 35,785 km, we computed the elevation angles at sea level (h_u = 0) and at h_u = 4.4 km (Mt. Whitney, the highest point in CONUS). The resulting elevation angles as a function of α are shown in Figure 4. At this resolution, these elevations angles are indistinguishable. The largest loss in elevation occurs when the satellite is at the horizon, and the loss here is less than 0.01 degrees! Hence, altitude by itself has no significant effect on elevation angle to the WAAS satellite.

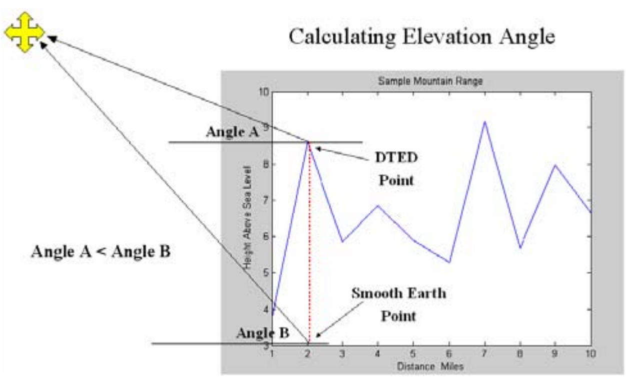

Figure 3 – Elevation angle decreases as the user height increases.

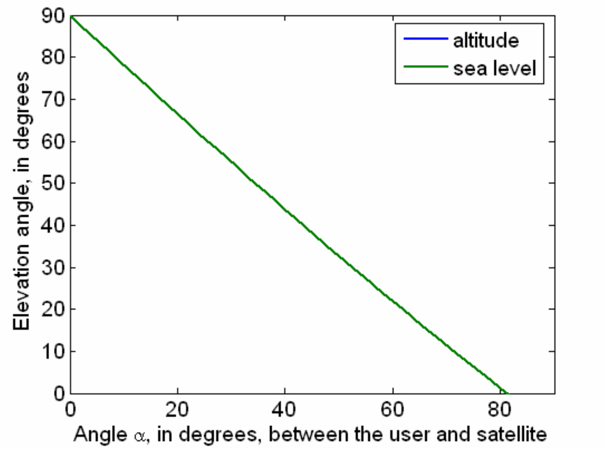

Figure 4 – Satellite elevation angle versus angle separating the user and satellite: user at sea level and user at 4.4 km altitude.

<u>Line of Sight Effects</u>

The significant effect of terrain on WAAS satellite visibility is due to shadowing in which higher terrain potentially blocks the user's line of sight to the satellite. A simple sketch of this appears in Figure 5. Fortunately, MATLAB contains a tool within its mapping toolbox to compute this directly from a digital terrain map. To study this effect for WAAS availability, we need an accurate model of the local terrain about the user's position.

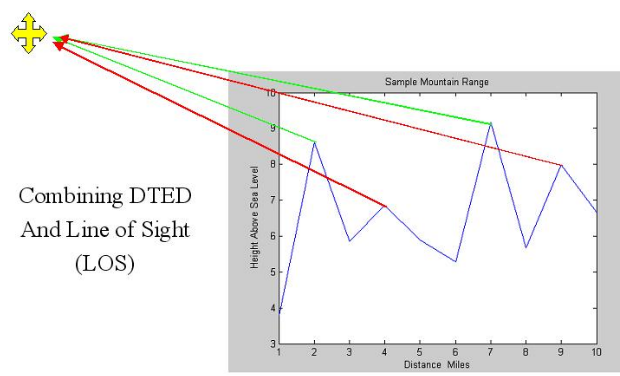

Figure 5 – The line of sight issue – satellite visibility suffers due to uneven terrain characteristics.

The Digital Terrain Elevation Data (DTED) database can be used to provide the required local terrain information. A 1 degree by 1 degree sample of DTED Level 1 for the San Francisco area is shown in Figures 6 and 7; Figure 6 shows this data as a MATLAB mesh plot, Figure 7 is a more typical topographical plot (logistically, DTED only contains data for square regions containing land masses – to create this map, zeros were appended for the missing ocean data).

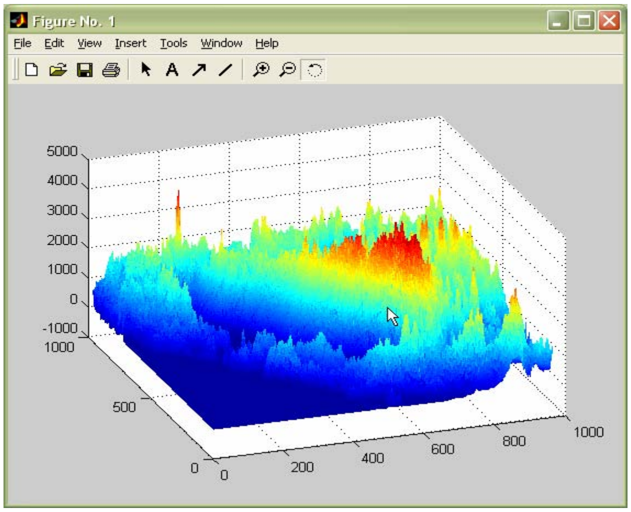

Figure 6 – DTED elevation data over a 1 by 1 degree grid for the San Francisco area – mesh plot.

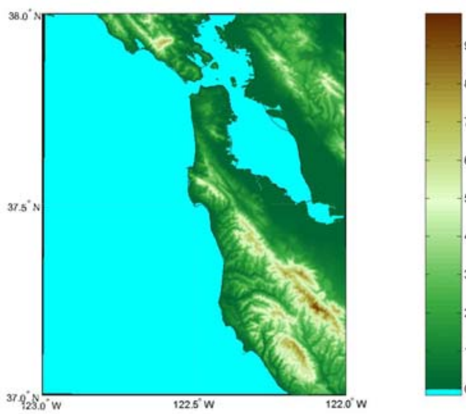

Figure 7 – DTED elevation data over a 1 by 1 degree grid for the San Francisco area – topographical plot.

<u>The GUI Tool</u>

To ease the use of the above calculations, an easy to use environment was needed. The GUI, created in MATLAB with an example shown in Figure 8, was designed to display as much as possible without overwhelming the use. The top left hand side of the GUI contains a Mercator projection of the world. This picture initially shows the entire globe, but can be zoomed in for locating the user's position. On this projection, the user's position is displayed as well as the satellites being looked at and their range rings (using a spherical Earth model). On the upper right hand side of the GUI, computed data is displayed. The elevation angle to the user is displayed across the top starting with the Pacific and Atlantic satellites, followed by three other possible satellite locations. Below this, the direct visible distance from the user to the satellite is displayed.

Changeable parameters are located in the center of the GUI on the right. Here you can change the range ring sizes from full horizon to minimum elevation angle of 5 to 25 degrees. You can also change the height of the satellite and the height of the user's antenna vertically (above the Earth's surface). In the center is also displayed the user's height above sea level in feet or meters.

On the bottom of the GUI reside entry boxes for the positions of three additional satellites, the user's position, and check boxes to enable the display of range rings for the Pacific and Atlantic satellites. The bottom left of the GUI contains a window to display a 1 by 1 degree grid of elevation angles. This picture can be displayed with line of sight taken into account or not.

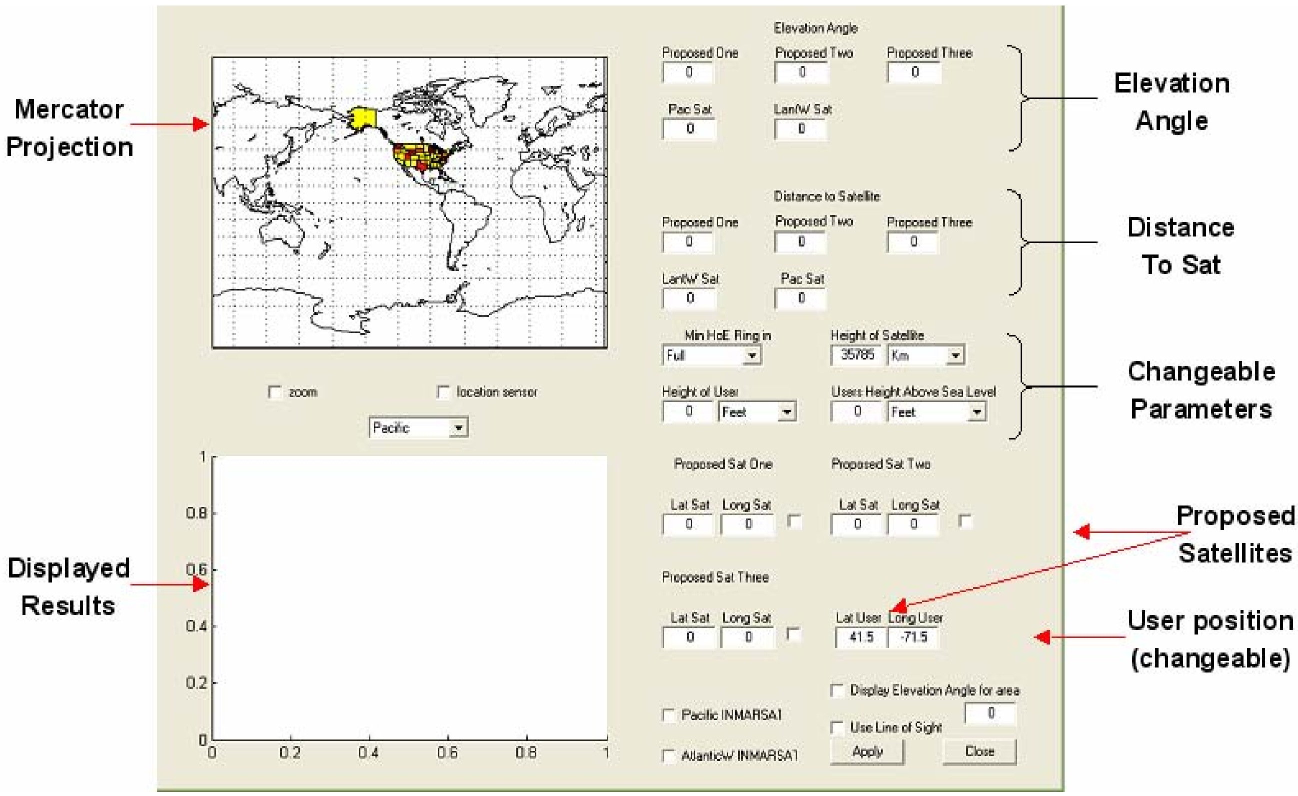

Figure 8 – The GUI tool.

RESULTS

To demonstrate the computation of line of sight for various terrain situations, we present a mix of examples: near Salt Lake City (a mountainous example which exhibits significant loss of satellite visibility), San Francisco Bay (which allows us to compare theoretical results to some recent field measurements), and Sault Ste. Marie (a location with higher latitude). In each case, a 1 degree by 1 degree area is considered.

Salt Lake City, Utah

The area about Salt Lake City exhibits significant mountainous terrain; hence, a great opportunity for loss of visibility of a satellite. Figure 9 shows the region under consideration (longitude 111W to 112W, latitude 40N to 41N).

In the northwest and southwest regions of this area we have two lakes. Moving eastward we have a mountain ridge that proceeds from north to south; a valley follows this. Finally on the east side of the region we have another mountain range.

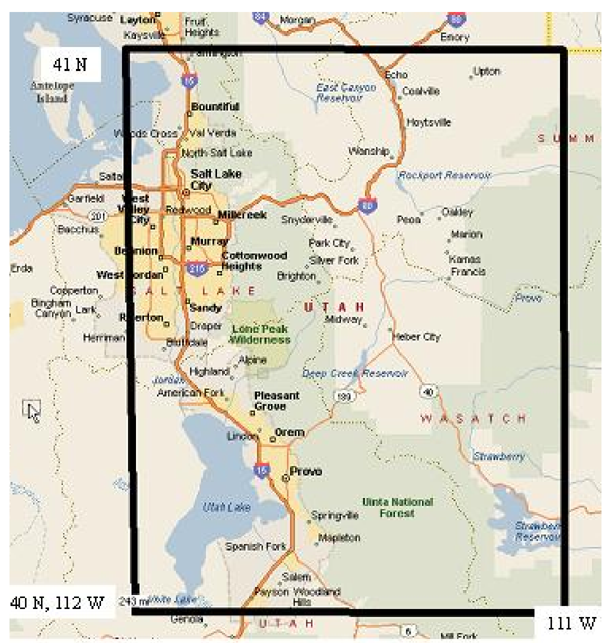

Figure 9 – Salt Lake City Utah region.

The terrain information from DTED was read and the elevation angles and line of sight were calculated for each point in the grid. Figure 10 shows the resulting elevation angle for the Pacific satellite. We note that this is as expected with most of the loss of visibility of the satellite (blackout – shown as white area) occurring on the eastern side of the mountain range. Figure 11 shows similar data for the Atlantic satellite, with the expected blackouts occurring on the western side of the mountains. There is less blackout for the Atlantic satellite because of its higher nominal elevation angle (~15.7º versus ~6º). Examining the data, the Pacific satellite calculation yields 27,758 points out of 59,081 points or 48 percent blackout in the Salt Lake City area. The Atlantic satellite calculation, on the other hand, yields 5,360 points out of 59,081 or 9 percent blackout. If we combine the two pictures to generate one that gives coverage based on visibility of either satellite, the result is only 1,947 points out of 59,081 or only 3.5 percent blackout in the region (shown as Figure 12).

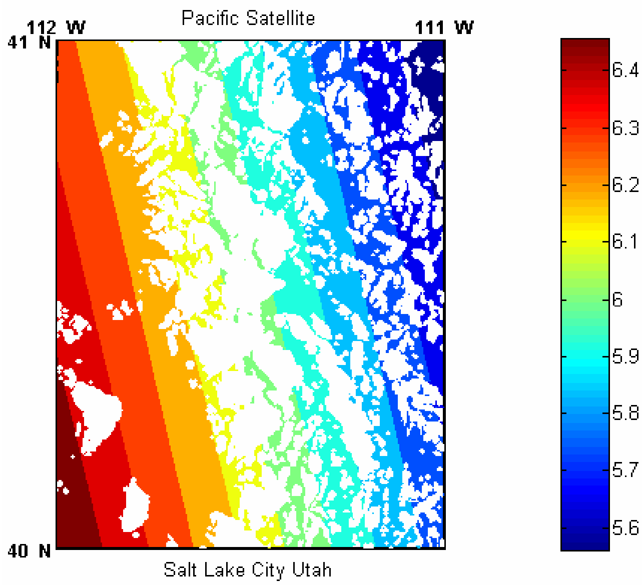

Figure 10 – Salt Lake City area, Pacific satellite, elevation angles and blackout areas (white).

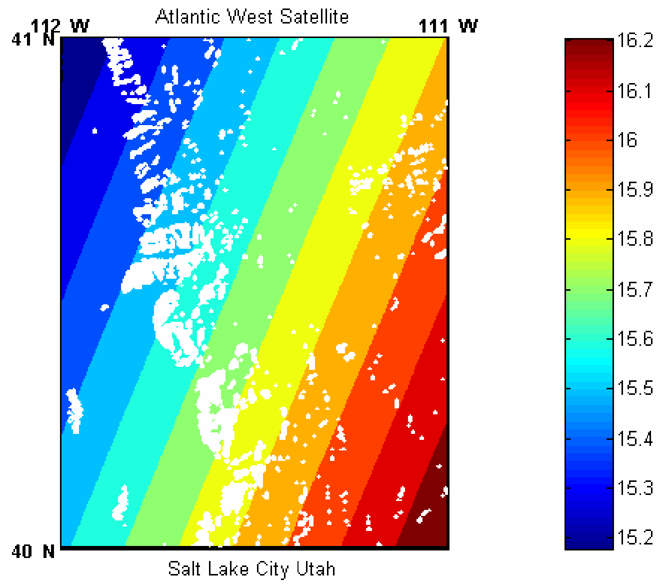

Figure 11 – Salt Lake City area, Atlantic satellite, elevation angles and blackout areas (white)

Figure 12 – White areas show where neither satellite is visible, Salt Lake City area.

<u>San Francisco Harbor – Theory</u>

Beyond its obvious maritime value, San Francisco is also an area of interest due to the size of the harbor, the hills and buildings of San Francisco that lay between the harbor and the Pacific satellite, and the mountain range to the east that could potentially block line of sight to the Atlantic satellite. The area looked at was from longitude 122W to 123W and latitude 37N to 38N. This gave us a clear picture of the harbor as well as a partial picture to the mountain range to the east, and the city to the west.

The line of sight calculations returned little blackout for either satellite. The Pacific satellite calculation yielded only 299 points out of 59,081, for 0.5 percent blackout; the Atlantic satellite calculation yielded 1,500 points out of 59,081, for 2.6 percent blackout. The surprising part about it was that all of the blackout locations occurred on land at this resolution (see Figures 13 and 14). Some blackout was expected along the eastern waterline of San Francisco due to the hills, but none occurred.

Our next step was to include the two new satellites going up plus the proposed third one. As stated before, the two new satellites are going up at longitudes 125W and 107W. The proposed satellite will be at 085W. By placing these three satellites in the sky, significant improvements are achieved in the elevation angles and visibility.

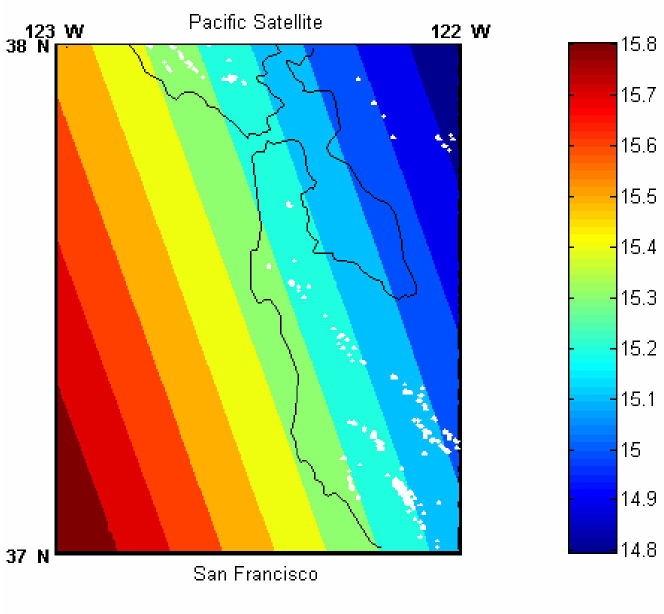

Figure 13 – Elevation angle to the Pacific satellite; black areas indicate no line of sight.

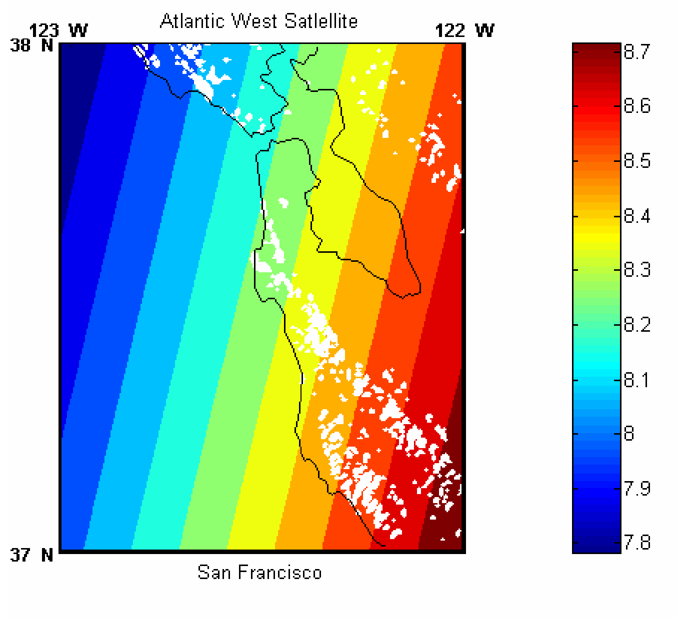

Figure 14 – Elevation angle to the Atlantic satellite; black areas indicate no line of sight.

The number of blackout areas in this case is reduced from approximately one-thousand to zero with the three new satellites. Elevation angles increase from 15 and 8 degrees, respectively, to 46, 43, and 31 degrees. Not only does this get rid of the blackout areas, but it provides redundancy in the system and allows for double and sometimes triple coverage in areas (elevation angle plots for these three satellites appears as Figures 15, 16, and 17).

<u>San Francisco Harbor – Measurement</u>

Figure 18 shows a larger scale area of San Francisco harbor depicting actual WAAS observations in 2004. In this picture the blue points indicate locations where at least one current WAAS satellite was visible to the user's receiver; the red points indicate those spots where the receiver indicated that no satellites were visible. One problem with this picture is that, due to the scale, it is difficult to see what is actually going on. You are not able to see that the red and blue dots are intermingled in some areas. Hence, we zoom in.

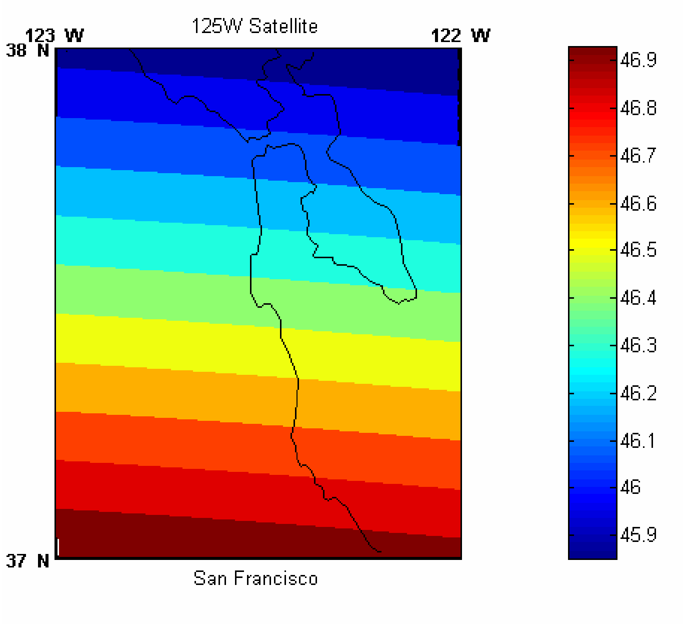

Figure 15 – Elevation angle to the 125W satellite.

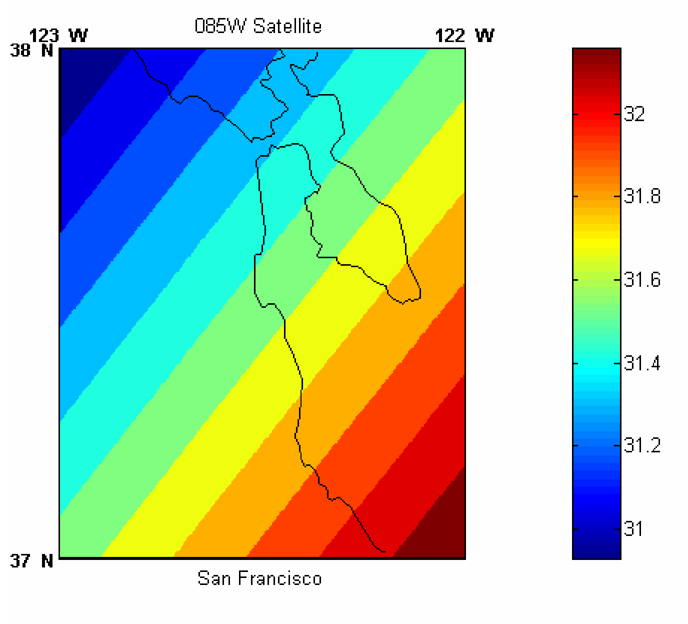

Figure 17 – Elevation angle to the 085W satellite.

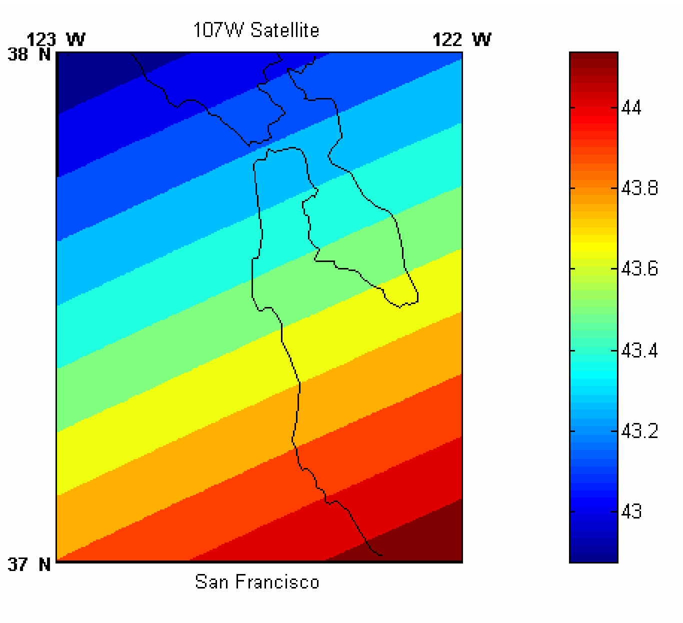

Figure 16 – Elevation angle to the 107W satellite.

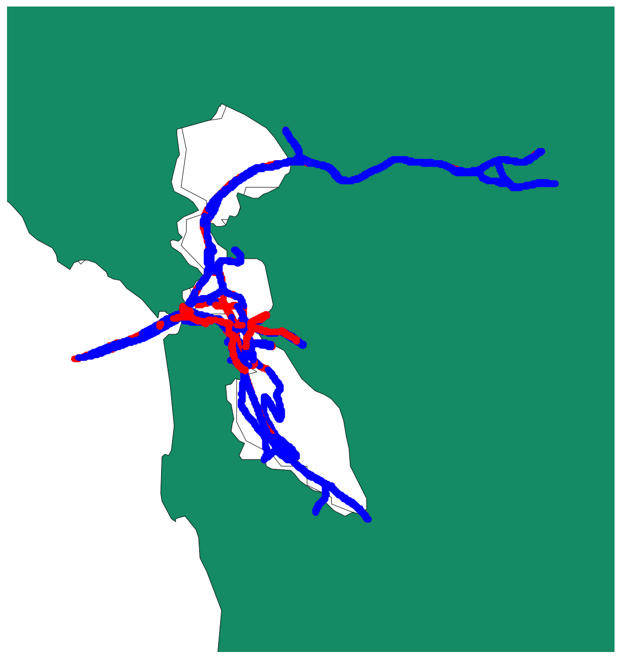

Figure 18 – Actual data from San Francisco harbor.

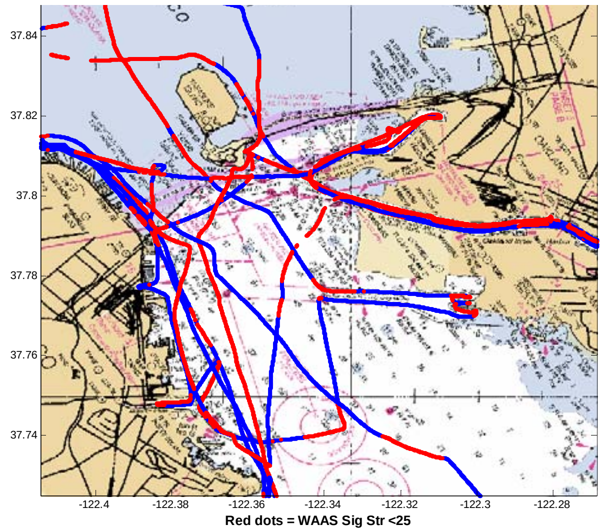

Figure 19 – Actual data from San Francisco harbor, zoomed.

Figure 19 zooms in on part of the harbor. In this figure we can see that the red and blue points are mixed throughout the trips that were traveled to collect the data. While this allows us a clearer picture of what was happening on the traveled legs, it also begs more questions. It is clear that east/west and north/south legs were made on this data collection mission. But, for example, on the east and west legs, you get conflicting results on WAAS availability. One leg says you have coverage from the satellite while the other says there is none. This is observed on the north and south bound legs also, and rules out terrain as a factor.

These abnormalities could be attributed to a several causes. There could have been other types of obstructions such as a bridge being passed under or a boat/tanker that passed by blocking the path. Also, the position of the antenna on the vessel could have played a role as the vessel rocked back and forth. (Figure 20 shows the vessel employed and the antenna position).

The theoretical results elevation angle match up pretty well with the measured data. The average measured elevation to the Atlantic satellite was 8 degrees; the calculations above yielded a range of 8.1 to 8.6 degrees. For the Pacific satellite, the measured data averaged 15 degree elevation; the calculation ranges from 15 to 15.2 degrees. The only difference is the percentage of coverage. The measured data had coverage at roughly 75% of the time, while theoretical data had coverage at 100% in the harbor.

Sault Ste. Marie

After looking at the San Francisco area, a location on the outer fringes of the Atlantic West satellite and further up north was considered. This area was Sault Ste. Marie (map in Figure 21). It spans from 084W to 085W longitude and 46N to 47N latitude. At this location the Pacific WAAS satellite is not visible at all, 13 to 14 degrees below the horizon; the Atlantic West satellite has an elevation angle from 28 to 29 degrees had no areas of blackout (see Figure 22).

Similar results occur for the proposed satellites. They exhibit no areas of loss of line of sight from the user to the satellite. While our calculations show no blackout areas to the Atlantic West satellite, the proposed satellites will provide redundancy and multiple coverage for the Sault Ste. Marie area.

Figure 20 – Antenna location on research vessel.

Figure 21 – Sault Ste Marie.

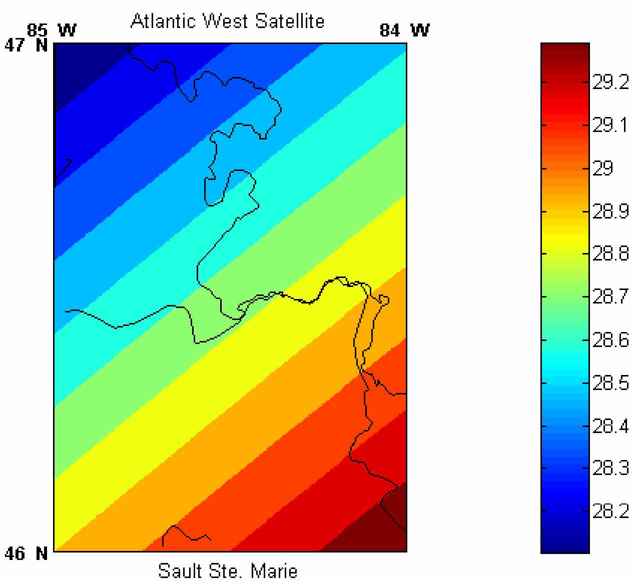

Figure 22 – Elevation angle to the Atlantic satellite; no loss of visibility due to terrain.

CONCLUSION

A tool for determining coverage (visibility) areas for WAAS throughout the continental United States has been developed. This was implemented using MATLAB and DTED. The system's results matched well with data that was collected in San Francisco harbor.

Currently the system has a hard time distinguishing waterways from land once you move inland. This is due to DTED only reading heights of land/water above sea level, not differentiating land and water. So, if the land surrounding a lake or river is only a few feet higher, then the data for the area will bleed together on the images created. Data can still be extracted for waterways and lakes, but you must know the exact latitude and longitude you want to look at.

The three proposed satellites to be launched later this year and early next year provide excellent redundancy to the current two satellites. They increase the average elevation angle for an area by as much as 25 degrees in some spots. Also by increasing the elevation angle, they reduce the number of blackout areas throughout the continental United States significantly.

FUTURE WORK

There are a few things that could be looked at in future studies in this area. First is building effects. The current DTED model does not take into account buildings; the height above sea level in major cities ignores the buildings (e.g. compare Manhattan and Central Park). So, 100-500 feet of additional "dirt" could to be added to the landmasses around harbors and bays before recomputing elevation angles and testing line of sight. If blackouts did occur, this would show that the surrounding cityscape could affect the coverage of WAAS in the area.

Next, the data collected from San Francisco should be verified. The existing data, with 25% blackout of WAAS, was only taken once and not repeated to see if the consistent results were obtained.

A method to distinguish water from land needs to be explored for ease of reading the data results for inland locations. It would also allow for more accurate reading of the data to see if blackout areas are actually in the harbor areas or on the land. This tool that was developed is not limited to maritime navigation applications; it could be used for land use as well as on the water.

Finally, computer issues need to be addressed. It currently takes 90 minutes to calculate coverage for a one by one degree longitude/latitude grid on a 2 GHz Pentium 4 (full resolution for line of sight, but location choices decimated by a factor of 5). To run the entire one by one grid when not decimated would take a couple of hours.

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